ACTS Mobile Terminals

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ABSTRACT

The development of the Advanced Communications Technology Satellite (ACTS) Mobile Terminal (AMT) and its follow-on, the Broadband Aeronautical Terminal (BAT), have provided an excellent testbed for the evaluation of K- and Ka-band mobile satellite communications systems. Such systems have proven viable for many different commercial and government applications. Combining emerging satellite communications technologies such as ACTS' highly focused spotbeams with the smaller, higher-gain K- and Ka-band antenna technology, results in system designs that can support significantly higher throughput capacity than today's current commercial systems. An overview of both of these terminals is presented in this paper.

INTRODUCTION

Since the early 1980's, NASA, through the Jet Propulsion Laboratory (JPL), has been involved in the development and demonstration of system concepts and high risk technologies to enable the introduction of commercial mobile satellite services (MSS). Initial' efforts focussed primarily on L-band [1], and currently commercial L-band MSS are available through several U.S. and international companies. However, it is expected that L-band will become saturated with MSS by the turn of the century. In view of this, NASA and JPL have focused on evaluating K- and Ka-bands for future MSS expansion.

K- and Ka-bands have outstanding potential for higher data rate communications and more highly diversified MSS for a number of reasons. Unlike L-band, K- and Ka-bands have a large bandwidth (500 MHz) already allocated for MSS services (WARC '92). Moreover, these higher frequencies support antenna designs which are physically smaller and have higher gains than lower frequency designs, K/Ka-bands, therefore, are excellent candidates for the pursuit of larger capacity services for commercial users (e.g., compressed video). However, satellite communications system design in these bands poses significant technical challenges for several reasons: (1) RF design is more challenging due primarily to lossy RF components, (2) significant atmospheric attenuation effects are present (e.g., rain attenuation), and (3) there are potentially large frequency uncertainties due to vehicular induced Doppler and oscillator stabilities.

NASA has provided a platform for the initial evaluation and exploitation of K/Ka-bands through its development of the ACTS. NASA/JPL has focused on overcoming the technical design challenges and providing a system architecture that exploits all of the benefits derived from K/Ka-band communications. The ACTS Mobile Terminal (AMT) is a fully tested, mobile satellite communications terminal that has been used in a variety of application specific experiments and demonstrations since December 1993 **[2,3].** Development of a follow-on higher data rate terminal, the Broadband Aeronautical Terminal (BAT), has recently been completed and numerous experiments and demonstrations are already underway. Details relating to the design and development of the AMT and BAT are presented in this paper.

ACTS MOBILE TERMINAL

The AMT incorporates system and subsystem solutions that have been devised to overcome the challenges of K- and Ka-band mobile satellite communications. The operational configuration utilized by the AMT is shown in Figure 1. A fixed station (or hub) communicates through the satellite with a mobile terminal. In this frequency division multiple access scheme, an unmodulated pilot signal is transmitted from the fixed station to the mobile terminal user through ACTS[1]. The pilot is used by the mobile terminal to aid antenna tracking, and as a frequency reference for Doppler offset correction and pre-compensation. For system efficiency, the pilot signal is only transmitted in the forward direction (fixed to mobile), Hence for the setup with the AMT, two signals exist in the forward direction, the pilot signal and the data signal. In the return direction (mobile to fixed) only the data signal is transmitted. Transmissions from both terminals occur in the band 29.634 GHz +/-150 MHz. The satellite is operated in a bent pipe mode, and transmissions from the satellite are in the band 19.914 GHz +/- 150 MHz. The operational data rates fo which the terminal was initially designed for range from 2.4 to 64 kbps. During the experiments, as will be discussed later in this paper, hi-directional data rates of 768 kbps have been achieved.

The block diagram of the mobile terminal is provided in Figure **2.** The architecture of the fixed station is identical to that of the mobile terminal with the primary exception of the antenna and the power amplifier. The mobile terminal utilizes a low-profile, tracking elliptical reflector antenna, while the fixed station has a stationary, high gain, 2.4 meter parabolic dish. For power amplification, the mobile terminal contains a 10 Watt traveling wave tube amplifier (TWTA)[2], and the fixed terminal a 65 Watt TWTA. Descriptions of the subsystems that comprise the mobile and fixed terminals are presented in the remainder of this section.

' With simple modifications, the pilot channel maybe used for information transfer.

[2] The baseline terminal design calls for a 1 W power amplifier.

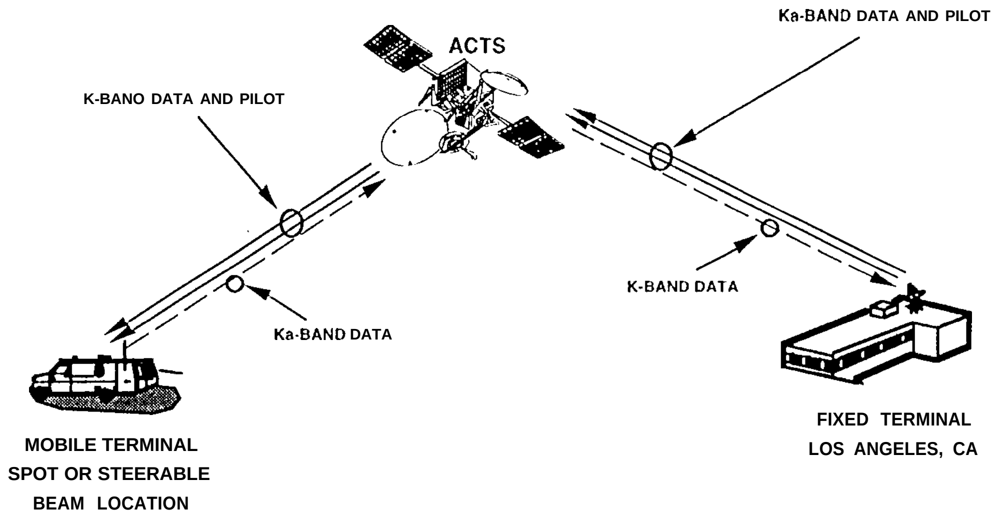

Figure *1* AMT Experiment Configuration

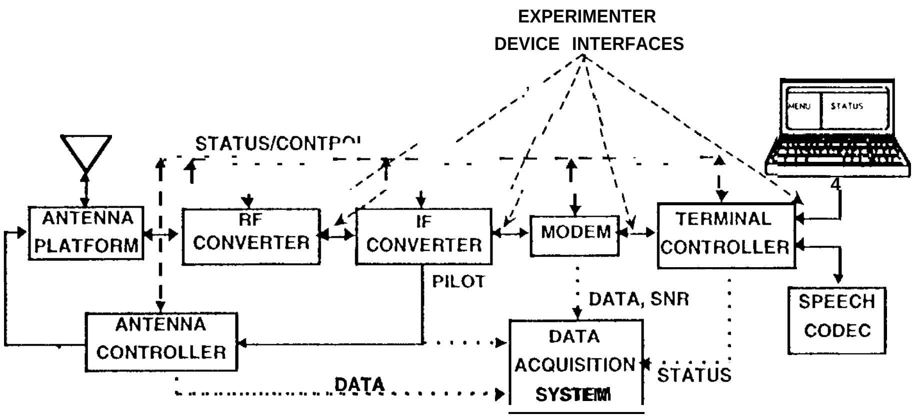

Figure 2 AMT Block Diagram

Speech Codec

The **speech codec is comprised of a handset, a main processing unit,** speech compression boards, and for the fixed station codec, a telephone line interface. The handset provides an audio and control interface for the user. In the case of the mobile terminal it is also used as the input device for dialing information. The main processing unit supports four interfaces. Three of these interfaces are: audio input from and output to the handset; audio record and play to a digital audio tape deck; and a telephone line interface. The fourth interface is to the terminal controller, consisting of digital data and control lines, for passing data back and forth to the terminal, and for codec control.

The coding of the voice signal is accomplished using independent microprocessor based encoder and decoder boards developed by Motorola. Three different data rates are supported: 9.6 kbps (Motorola MRELP), 4.8 kbps (U.S. Government standard CELP), and 2.4 kbps (U.S. Government standard LPC-10). The voice quality ranges from near toll to communication quality, and generally improves monotonically as the data rate increases. The operational Bit Error Rate (BER) is specified to be less than or equal to 10-3,providing little or no perceptible degradation in voice quality. Re-synchronization from outages due to shadowing occur within 350 milliseconds.

The use of these independent encoding and decoding boards allows for different data rates on the receive and transmit links. This allows for signal power compensation to combat rain attenuation via real-time data rate changes. Switching time between these rates occurs **in less than 100 milliseconds.**

Terminal Controller

The terminal controller has four main tasks: (1) coordinate the AMT subsystems, (2) direct the point-to-point communications operation of the link, (3) provide status and terminal information to the data acquisition system for recording, and (4) provide a user interface. The terminal controller monitors and controls certain aspects of the **speech codec, modem, IF converter, RF converter, and antenna controller subsystems.** The terminal controller is also capable of supporting external devices through the use of one of its serial RS-232 ports. The terminal controller functions include: data rate specification (with the speech codec and modem), automated data rate changes (with speech codec and modem) as part of a rain compensation algorithm [4], manual and automated antenna pointing control, data generation and capture (both repetitive patterns and PN sequences), BER calculations, system monitoring, transmit and receive frequency control, and output power specification, It also contains the algorithms that translate the communications protocol [5] into the operational procedures and interfaces among the various terminal subsystems.

For flexibility and to minimize development cost, the terminal controller was implemented using standard VME off the shelf hardware. It resides in a seven slot VME chassis, and consists of four VME boards.

Modem

An all digital low rate modem suitable for use in the land-mobile satellite communications channel was developed for use with the terminal. In addition, a commercially available coherent modem was procured to provide higher data rates in certain applications. This latter modem has also been used in the land-mobile experiments and is described in the BAT section of this paper, The design of both modems were simplified by the fact that due to the antenna directivities, the channel may be approximated by a shadowed Rician channel with K=30.

The baseline modem developed is a multi-rate DPSK modem that transmits and receives at 2.4/4 .8/9.6 and 64 kbps. A functional block diagram of this modem is illustrated in Figure 3. The modulator receives digital data from the terminal controller, and encodes the data using a rate 1/2, constraint length 7 convolutional encoder. The encoded symbols are interleaved to protect against burst errors and a synchronization word is inserted in the symbol stream to allow the demodulator to find the interleaver boundaries at the beginning of a transmission, After the synchronization word is inserted, the symbol stream is differentially encoded and used to phase modulate **a 70** MHz carrier (resulting in a square wave pulse shape) which is output from the

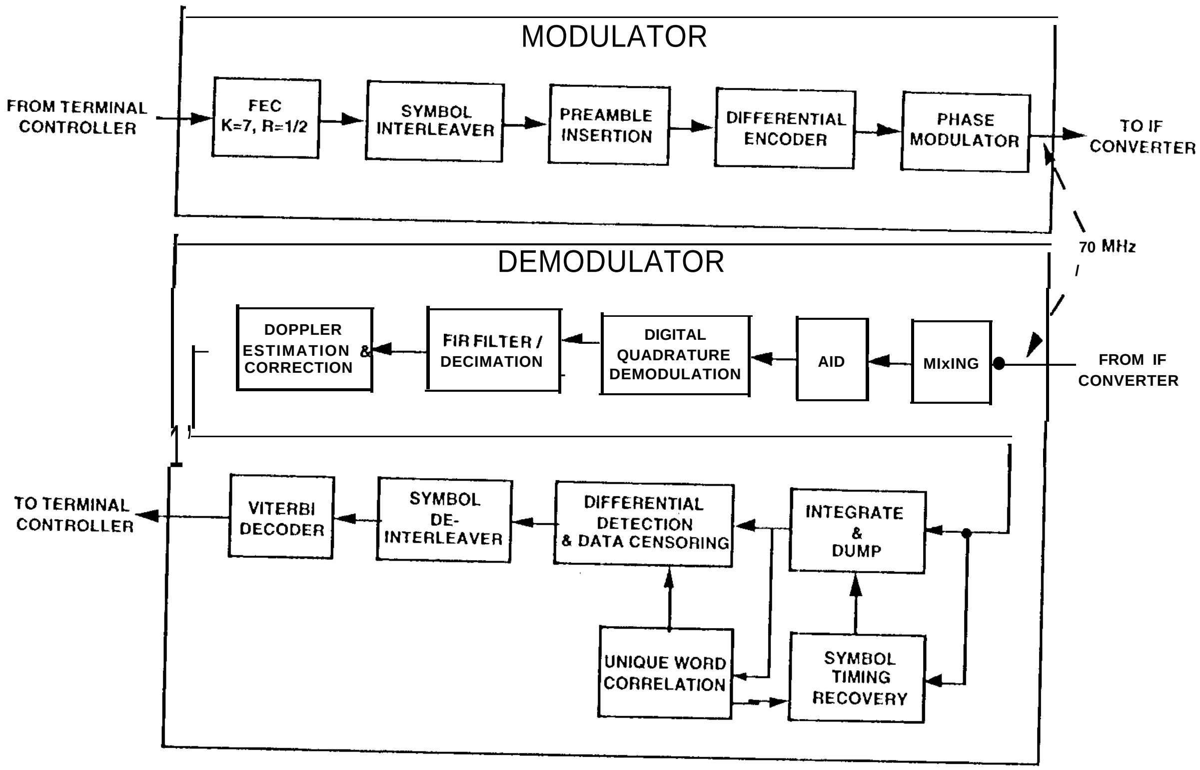

Figure 3 Baseline DPSK Modem Functional Block Diagram

modulator to the IF converter. The input signal to the modem from the IF converter is also at a 70 MHz IF, with a 30 MHz bandwidth,

The front end of the demodulator mixes the 70 MHz received signal down to 768 kHz. This mixing stage also filters the received signal using switchable filters to prevent noise from aliasing in-band when it is digitized and decimated. A bandpass filter with a 1 dB bandwidth of 264 kHz is switched in when the data rate is 64 kbps. A bandpass filter of 84 kHz is switched in when the data rate is 2.4, 4.8, 9,6 kbps. After this analog mixing stage, the 768 kHz signal is digitized using a 12 bit analog-to-digital converter. The digital signal is then passed to the digital front end where digital quadrature demodulation results in a baseband signal, This signal is decimated and low pass filtered with a FIR filter and then decimated again.

After the FIR filter, the received signal is used to estimate the frequency offset and correct the received signal accordingly. This algorithm has been designed to handle frequency uncertainties on the order of 10 kHz changing at a maximum rate of 350 Hz per second [6]. After correcting the frequency offset the signal is passed to the symbol timing recovery subsystem which recovers the timing from a noisy signal utilizing an open-loop delay and multiply technique. This symbol timing algorithm was chosen for its ability to operate in the mobile satellite communications environment, i.e., robustness in an environment that contains frequent deep, short term signal fades, The symbol timing is then used to control the integrate and dump filter. After the integrate and dump filter operation, the synchronization word is detected and stripped from the symbol stream, the symbols are deinterleaved and decoded using a Viterbi decoder. The decoded data is then output to the terminal controller. The performance specification of the modem is a bit error rate of 10-3 at an E_b/N_o of 7,0 dB in an AWGN environment including modem implementation losses.

The majority of the processing in the modem occurs in programmable digital signal processing chips - the Texas Instruments TMS320C50 chip. A board that contains six of these chips and a Viterbi decoder chip was designed and used for this modem,

/F Converter

The IF upconverter converts the modem output at low a IF (70 MHz) to a high IF at 3.373 GHz (nominal). The IF downconverter performs the reverse operation, i.e., it translates the received signal at the output of the RF downconverter from 3.373 GHz (nominal) to a 70 MHz IF that is input to the modem. The input bandwidth of 30 MHz at 70 MHz from the modem is converted to one of 6000 channels in a 300 MHz bandwidth centered at 3.373 GHz. On the receive side, the inverse operation is performed. The selection of the transmit and receive frequencies can either be performed by the terminal controller or through a series of thumbwheel switches located on the front panel of the IF converter, For the fixed terminal, the IF converter also sums in a pilot tone at 3.370 GHz for transmission over the link.

A key function of the IF converter in the mobile terminal is pilot tracking and Doppler pre-compensation. The down-converted pilot is tracked in a dual bandwidth phase-locked loop and may be used as a frequency reference in the mobile terminal. The output of the phase-lock loop is also used to generate a reference for the upconversion stage to precompensate the transmitted signal from the mobile terminal for the estimated Doppler on the return link. These functions are all performed in analog hardware. A block diagram of this portion of the IF converter is shown in Figure 4. Finally, the IF converter provides both the demodulated pilot and noncoherent received pilot power to the antenna controller, terminal controller, and the data acquisition system, for use in antenna acquisition and tracking, operation of the communications protocol, and propagation analyses.

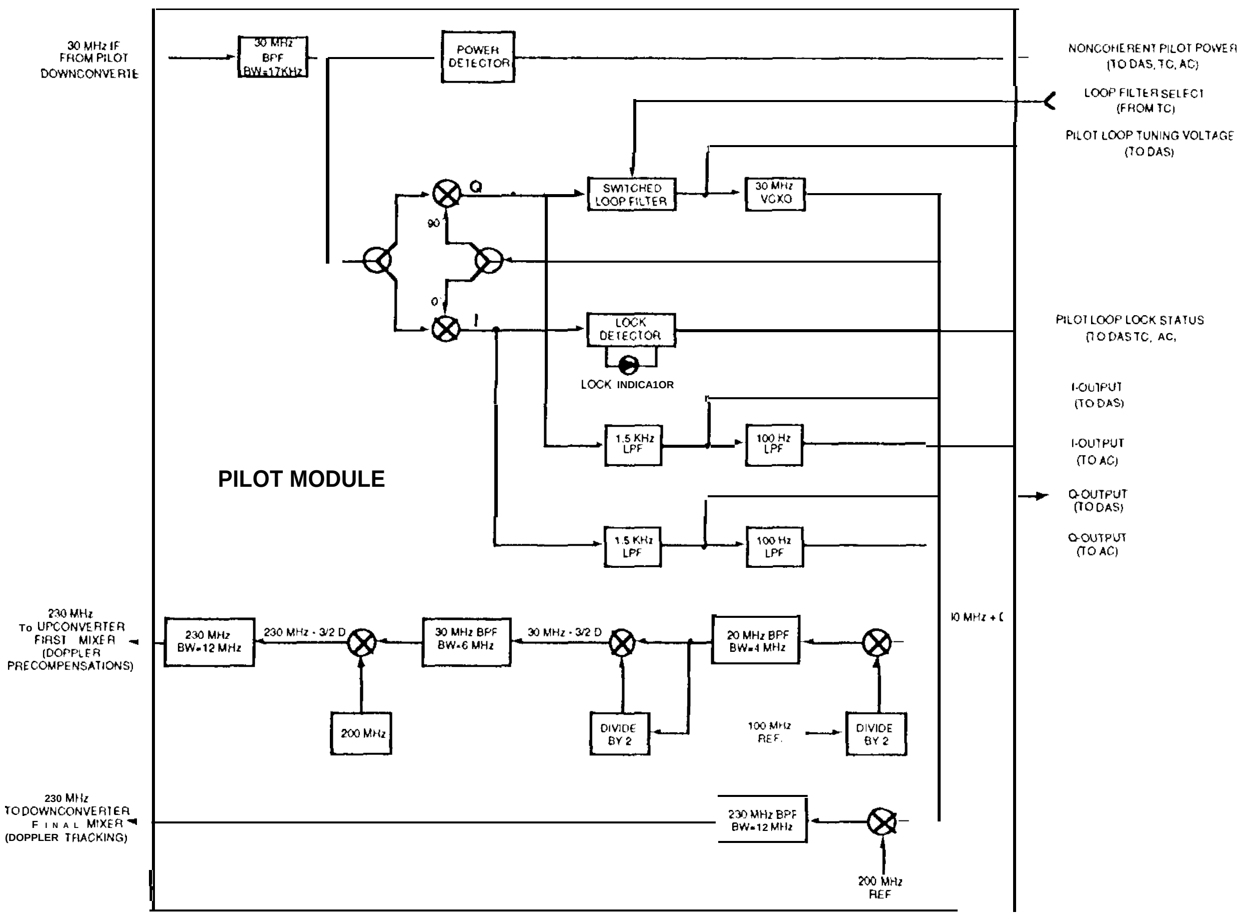

Figure 4 IF Converter Phase Lock Loop and Doppler Precompensation

RF Converter

The RF upconverter provides the frequency and power translation for the modulated IF signal from the IF converter centered at 3.373 GHz +/- 150 MHz to the transmit frequency and power level required at 29,634 GHz +/- 150 MHz. It also provides the necessary power amplification for use with a passive antenna. Power monitoring and control is provided to the AMT terminal controller, The RF downconverter provides the frequency and power translation for the **received** RF signals at 19.914 GHz +/- 150 MHz from the antenna subsystem to a center frequency of 3.373 GHz +/- 150 MHz.

Reflector Antenna

Development of K/Ka-band antenna technology is one of the key objectives of the AMT project. The benefits of a K/Ka-band antenna design include higher antenna gain and/or a substantial size reduction compared to lower frequency bands. A "passive" elliptical reflector-type antenna **[7] to** be used in conjunction with a separate high power amplifier, low noise amplifier, and diplexer was the preferred design approach, and was the primary antenna used in the initial land-mobile experiments. The development of an active receive array and the aeronautical antenna, both of which may be used for land-mobile applications, are described in later sections.

The antenna subsystem satisfies the following design specifications: (1) the antenna was designed for the rugged vehicular environment; **(2) initial satellite acquisition** occurs within 10 seconds (unobstructed signal path); (3) the transmit/receive minimum gain specifications are met for vehicle turn (yaw) rates up to 450/second and pitch and roll up to +/-6°; (4) the tracking system maintains point during signal outages of up to 10 seconds; (5) the transmit gain at 29.634 +/- 0.15 GHz is a minimum of 20.1 dBi over a 12° elevation beamwidth[3] for elevation angles between 30° and 60°; (6) the receive gain at 19.914 +/- 0.15 GHz is a minimum of 18.8 dBi over a 12° elevation beamwidth[4] for elevation angles between 30° and 60°; and (7), the minimum receive system G/T is better than -6 dB/°K over the elevation beamwidth. The receive system noise temperature, as measured at the bottom of the rotary joint is 335° K (the noise figure of the LNA is 2.5 dB). The antenna has minimal cross-polarization and sidelobe levels no greater than -15 dB.

The input power to the antenna assembly may be as high as 10 W, with no degradation of the receive performance. The reflector resides inside an ellipsoidal water-repelling radome of outside diameter approximately 8 inches (at the base) and maximum height of approximately 4 inches. A block diagram indicating the components of the antenna subsystem is shown in Figure 5. A picture showing the reflector antenna is presented in Figure 6.

For satellite acquisition, the antenna subsystem performs a sky search, using the noncoherent received pilot power. Once the satellite has been acquired, an inertial

[3] The peak gain is 22.8 dBi.
[4] The peak gain is 22.3 dBi.

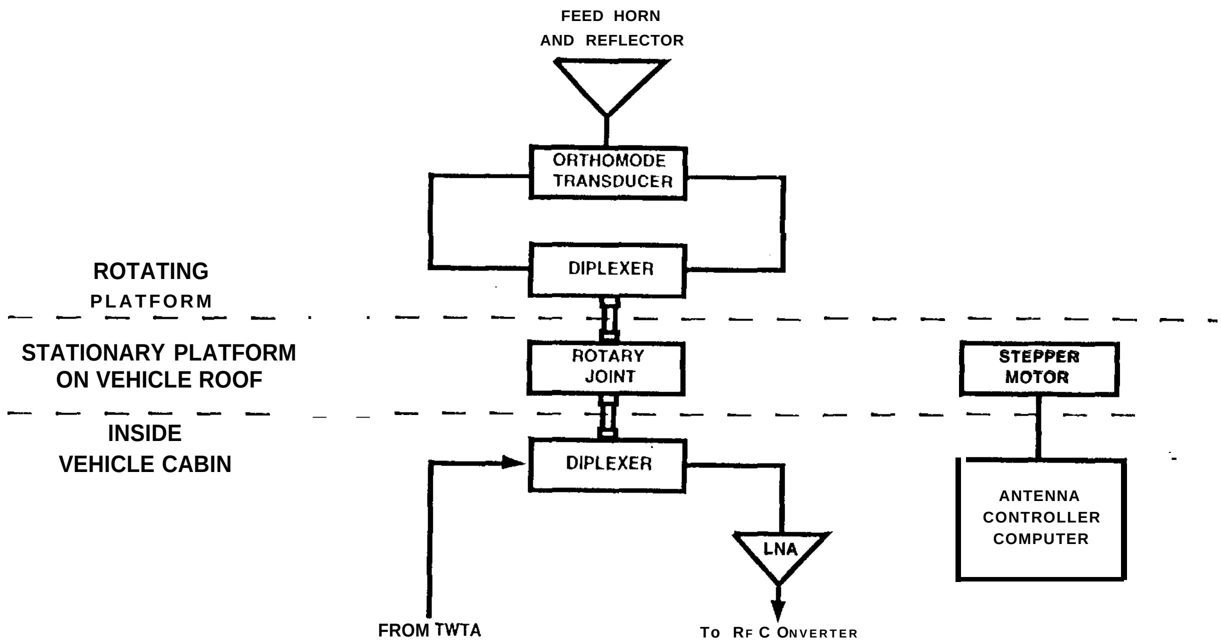

Figure 5 Small Reflector Antenna Subsystem Components

Figure 6 Small Reflector Antenna

vehicle yaw sensor provides most of the information to keep the antenna pointed at the satellite, This is coupled with “mechanical dithering” of the antenna. For this, the antenna is smoothly rocked (dithered) side-to-side through a small angle (10, at a rate of 2 Hz while the signal strength of the received pilot tone is monitored. This mechanical dithering induces less than 0.3 dB amplitude and 0.2° phase variation on the received signals.

When the satellite line-of-sight is shadowed by an obstacle for a long time (greater than 30 seconds), such as when driving behind a building, the antenna may no longer be aligned with the satellite when the obstacle is cleared from the satellite view. The antenna subsystem will then re-initiate signal acquisition.

Active Receive Slot Array Antenna

In addition to the small reflector antenna, an active receive slot array antenna was also developed [8], The antenna operates at 19.914 +/- 0.15 GHz, and has a fixed angular beam region 46° above the horizon **(when the antenna is flat), with an elevation** beamwidth at least 12°, This antenna consists of an array of fourteen linear series fed type microstrip slot arrays, fourteen packaged Monolithic Microwave Integrated Circuit (MMIC) LNA submodules connected at each subarray output, a 14-way Wilkinson type power divider, and a final additional MMIC LNA submodule used as a driver amplifier. The measured G/T’ of the antenna is -8 dB/°K over the elevation beamwidth, and the beam peak is -6.4 dB/°K. When used in a mobile environment, satellite tracking is very similar to that used for the small reflector antenna, A picture of this antenna is shown in Figure 7.

Data Acquisition System

The Data Acquisition System (DAS) performs continuous measurement and recording for a wide array of propagation, communication link, and terminal parameters. A listing of the signals recorded with the appropriate sampling rates is presented in Table 1. Of significant interest is the simultaneous recording of the received pilot and the antenna boresight video. This latter recording comes from a separate platform that is mounted on the roof of the vehicle. This platform contains a video camera that is slaved to the communications antenna. This allows for correlation of the received signals with any obstructions that may be in the signal path - a significant aid in analysis of the propagation results. The DAS also provides real-time displays of these parameters to aid the experimentation in the field, The user interface to the DAS is through a touch screen on the DAS display. This feature makes for more efficient operation of this piece of test equipment while in the mobile environment. Mass data storage of up to 10 Gbytes of data on two separate 8 mm data tape drives is possible, providing up to 12 hours of continuous recording.

As with the terminal controller, the DAS was developed using commercially available VME components.

Figure 7 Active **Receive Array**

Table 1 Data Acquisition System Data and Sampling Rates

Signal Type	Terminal Location	Sample/Record Rate	Resolution (bits)	Interface
Received Data	Mobile, Fixed	2.4-64 kHz	1	TTL
Data Quality	Mobile, Fixed	2.4-64 kHz	7	TTL
Receive Power	Mobile, Fixed	2 Hz	28	IEEE-488
Transmit Power	Mobile, Fixed	1 Hz	12	RS-232
Transmit/Receive Frequency	Mobile, Fixed	Asynchronous	28	RS-232
Inphase Pilot	Mobile	4,8,12,16 kHz	12	AID
Quadrature Pilot	Mobile	4,8,12,16 kHz	12	AID
Non-coherent Pilot	Mobile	4,8,12,16 kHz	12	AID
Pilot PLL Tuning Voltage	Mobile	4,8,12,16 kHz	12	AID
Pilot Lock Status	Mobile	10Hz	1	TTL
Antenna Azimuth	Mobile	5 Hz	20	RS-232
Antenna Boresight Video	Mobile	128-384 kbps	8	RS-170
Vehicle Position	Mobile	1 Hz	28	G PS
Vehicle Velocity	Mobile	1 Hz	20	G PS
Vehicle Heading	Mobile	1 Hz	20	GPS
Terminal Status	Mobile, Fixed	Asynchronous	32	RS-232
Event Marker	Mobile, Fixed	Asynchronous	1	TTL
Transmit/Receive Audio	Mobile, Fixed	8 kHz	8	ANALOG

Terminal Integration and Test

An example of the performance expected over the satellite is illustrated by the conservative link budgets presented in Table 2 for the forward and return links. These link budgets were computed for a data rate of 4.8 kbps, a bit error rate of 10^{-3}, and the mobile' terminal in Denver, Colorado. The forward link budget is presented for the data signal only. In both directions there exist significant performance margins, which are generally exceeded when the favorable tolerances are considered. These performance margins include 3 dB of fade margin in each direction for mobile operations,

The initial characterization of the AMT performance was accomplished through a series of BER tests. Data of this nature was collected for all three of the lower operational data rates (2,4, 4.8, 9.6 kbps). BER values were recorded in the range from 10-5 to 10-1. The main specification that this terminal had to meet was a BER of 10“3 at an E_b/N_o of 9.0 dB or better. This BER specification was achieved at 6.5 dB, 6.5 dB, and 8.5 (E_b/N_o) dB for 9.6 kbps, 4.8 kbps, and 2,4 kbps, respectively, The significantly higher BER specification for the 2.4 kbps case is due to the performance of the Doppler estimation and compensation algorithm in the modem. A BER curve for the 9.6 kbps case is plotted as an example in Figure 8. A significant point to note is that the estimated phase noise and frequency offset degradation was found to be negligible.

Following baseline terminal performance characterization, the mobile terminal has been installed in multiple land-mobile platforms. The primary platform that the terminal has been installed in is an experimental van shown in **Figure 9. A picture showing some of the equipment layout in** the van is shown in Figure 10. This van has traveled throughout the continental United States to perform various experiments. Integration of the terminal in a military vehicle for an experiment is shown in Figures 11.

In each of the experiments performed, different equipment has been integrated at the experimenter points indicated in Figure 2. For example, in the experiment depicted in Figure 11, a military radio at 70 MHz was interfaced to the IF converter, and a multiplexer (voice and data) and a video codec were interfaced to the modem [9]. During another experiment, a UHF radio was interfaced to the speech codec allowing a nomadic user to communicate through the satellite. For a video broadcast experiment with NBC, the baseline AMT modem was replaced with a coherent modem (described in the BAT section) and compressed video was evaluated at rates up to 768 kbps. The AMT has even been used for control of a robotic vehicle [1 O], where the communications link using the point-to-point protocol (PPP) provided an ethernet extension between the robotic vehicle and a base station.

Table 2 AMT Experiment Link Budgets

PARAMETER	FORWARD LINK	RETURN LINK
	LA Fixed Station - Denver AMT	Denver AMT - LA Fixed Station
Terminal Transmitter Parameters		
EIRP, dBW	62.97	30.10
Pointing Loss, dB	-0.50	-0.50
Radome Loss, dB		-0.40
Path Parameters		
Space Loss, dB	-213.48	-213.48
Frequency, GHz	29.634	29.634
Range, km	38000	38000
Atmospheric Attenuation, dB	-0.36	-0.36
Satellite Receive Parameters		
Polarization Loss, dB	-0.50	-0.50
Pointing Loss, dB	-0.22	-0.22
G/T, dB/°K	20.56	19.41
Bandwidth, MHz	900	900
Received C/N_o, dB-Hz	97.12	62.70
Transponder SNR_{IN}, dB	7.58	-26.85
Limiter Suppression, dB	-1.05	-1.05
Transponder SNR_{OUT}, dB	6.53	-27.90
Satellite Transmitter Parameters		
EIRP, dBW	63.31	36.19
Pointing Loss, dB	-0.24	-0.22
Path Parameters		
Space Loss, dB	-210.03	-210.03
Frequency, GHz	19.914	19.914
Range, km	38000	38000
Atmospheric Attenuation, dB	-0.50	-0.50
Terminal Receive Parameters		
Polarization Loss, dB	-0.50	-0.13
Radome Loss, dB	-0.20	
Pointing Loss, dB	-0.50	-0.50
G/T, dB/°K	-6.00	27.85
Downlink C/N_o, dB-Hz	74.18	81.48
Overall C/N_o, dB-Hz	74.15	61.60
Required E_b/N_o (AWGN), dB (10^{-3} BER)	6.50	6.50
Frequency Offset Degradation, dB	0.00	0.00
Phase Noise Degradation, dB	0.00	0.00
Fade Allowance, dB	3.00	3.00
Data Rate, kbps	4.8	4.8
Required C/N_o, dB-Hz	43.31	43.31
Link Margin, dB	**27.84**	**15.29**

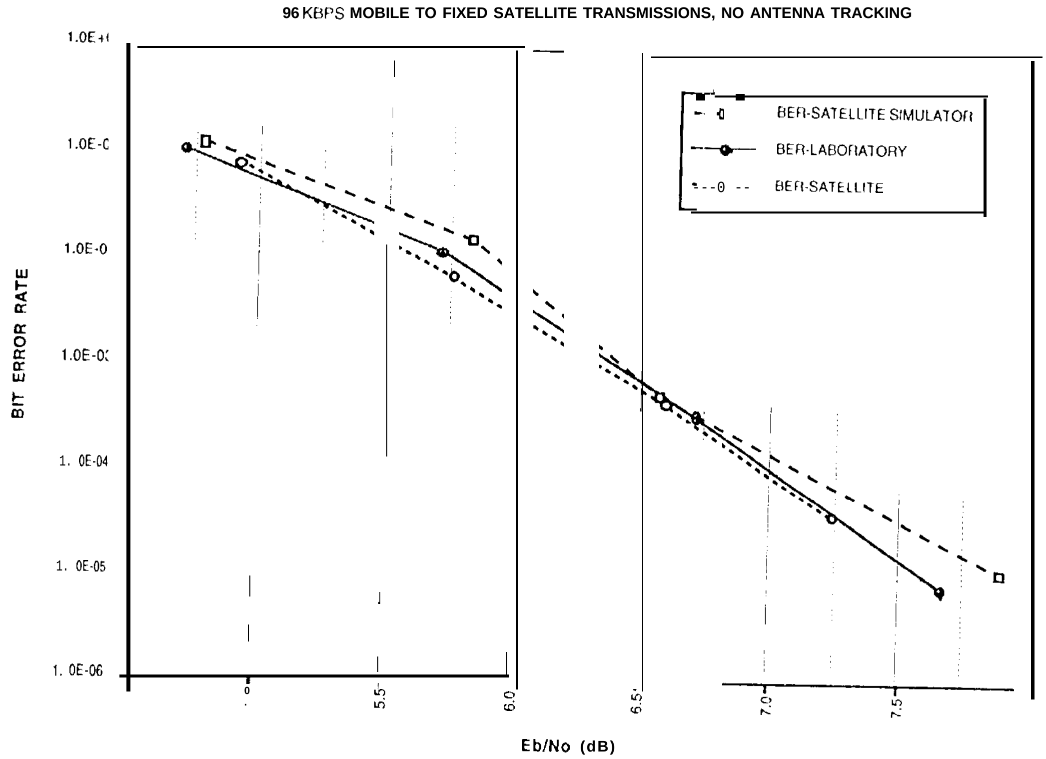

Figure 8 Mobile Terminal Performance

Figure 9 Baseline AMT Van

Figure 10 Baseline AMT Van Equipment

Figure 11 AMT Installed in Military Vehicle

BROADBAND AERONAUTICAL TERMINAL

Much has been learned about K/Ka-band mobile satellite communications channel through the various field tests and experiments that have been accomplished with the AMT. A natural extension of these experiments and the basic AMT design was to investigate aeronautical 20 and 30 GHz satellite communications. With several modifications to this design, much higher rate communication capabilities could be achieved for operation in the aeronautical environment. The resultant terminal, the BATII 1], provides full-duplex communications up to a data rate of 1.544 Mbps with a fully tracking antenna.

The specific experimental objectives with this terminal are to: (1) demonstrate and characterize the performance of high data rate aeronautical K/Ka-band communications, (2) characterize the propagation effects of the communications channel during take-off, cruise, and landing phases of flight, and (3) provide the systems/technology groundwork for an eventual commercial K/Ka-band aeronautical satellite communication system.

The system configuration for aeronautical operations is shown in Figure 12. The operation of this terminal differs slightly from that of the AMT. While the terminal is capable of using one of the high gain spot beams of ACTS, the primary satellite antenna used is the lower gain steerable beam. This antenna may be steered at up to 2° per second and provides coverage in any location visible to ACTS at 104° W longitude. With the steerable antenna, the aircraft may be tracked while in flight. To allow the satellite antenna to be used to track the aircraft, position information from the aircraft is multiplexed in with the data on the return link, and forwarded to the satellite control center. As the aircraft traverses the spot for the steerable beam, the satellite control center will position the steerable beam to keep the aircraft within the 1dB contour of the beam[5]. The operational up/down frequency bands and data/pilot transmissions are identical to those used for the AMT.

A block diagram of the BAT is presented in Figure 13. The terminal development leverages off the technologies developed under the AMT project. As such, the AMT RF converter and IF converter have been adapted from the AMT land-mobile design to operate in the higher dynamic aeronautical environment.[6] These two subsystems have been grouped in Figure 14 as the block converter subsystem. The AMT data acquisition system has also been modified for use in the BAT by developing the interface software to gather data from a new antenna controller. The antenna, power amplifier (100 Watts output RF power), modem, and video codec have been designed or chosen specifically for this application, and are described in the remainder of this section.

[5] The 3 dB contour of the beam has roughly a 200 mile diameter.

[6] Only the IF converter was modified to increase the pilot phase lock loop tracking bandwidth.

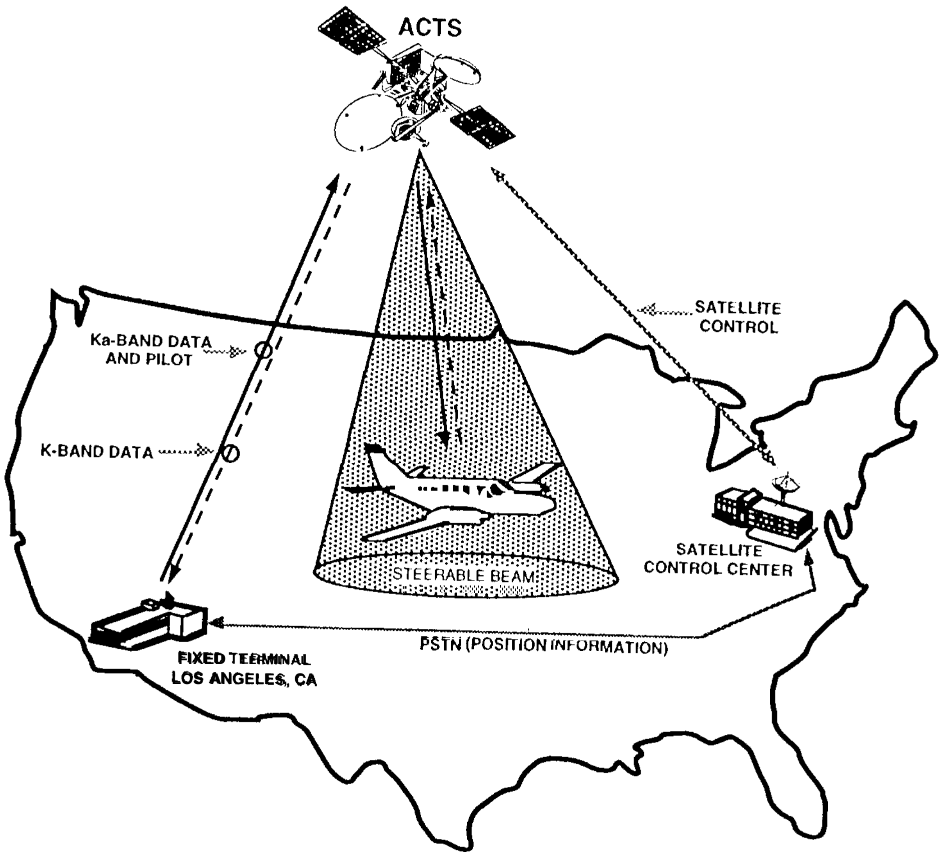

Figure 12 BAT Experiment Configuration

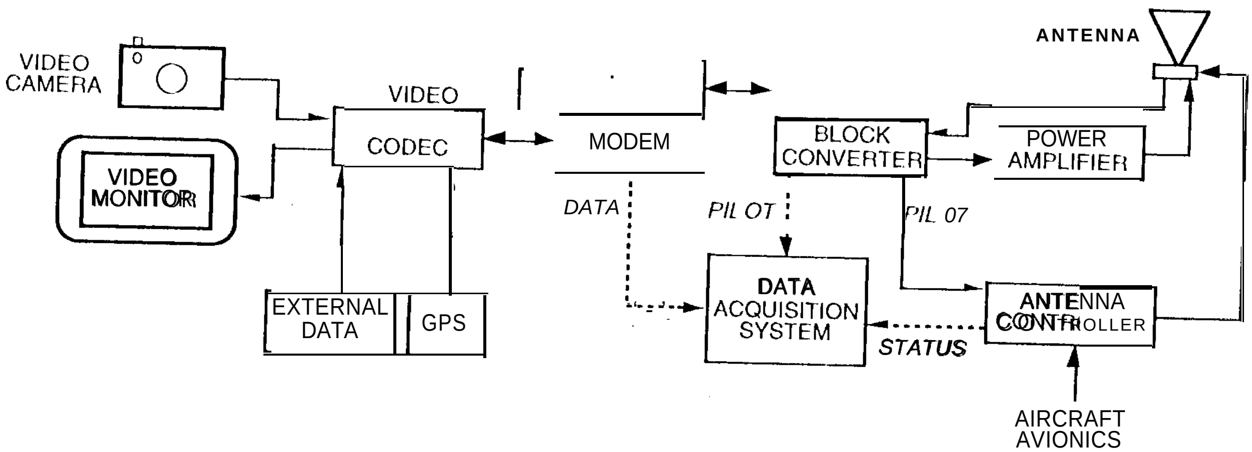

Figure 13 BAT Block Diagram

Video Codec

Since the BAT incapable of much higher data rates, high quality video transmission became a possibility. For this reason, various video compression algorithms were investigated for use with this terminal. These investigations were restricted to commercially available codecs. The requirements on the codec were that it provide compressed full motion video from 64-2000 kbps, and that it be capable of multiplexing in various types of data (e.g., aircraft position information) with the compressed video for transmission.

Current, commercial video codecs, designed for a rather benign hard wired communications environment, do not perform well in the mobile satellite communications channel. The aeronautical mobile satellite communications channel may have periods of signal outage due to aircraft structure shadowing or the antenna tracking keyhole effect[7]. Signal outages necessarily require the video codec to regain synchronization rapidly when the signal returns. The best outage recovery performance observed with existing video codecs was on the order of three seconds after the video codec started receiving valid data. In addition to signal outages, the channel typically exhibits a higher bit error rate than do the communication channels over which the video codec is ordinarily used. As a result, it is critical that the video codec degrade “gracefully” in the presence of high bit error rates, and again recover rapidly from these periods of errors. Other required video codec features that are a major consideration for aeronautical applications are that **the video codec be small in size, light in weight, somewhat rugged in construction, and capable** of **multiplexing multiple external data** sources with the compressed video data stream.

In evaluating the codec video quality, the performance at the data rates between 128 kbps and 384 kbps was deemed to be most important for the planned mobile satellite communications experimental applications, Most video codecs were found to provide very good quality video at data rates approaching TI (1 ,544 Mbps), but there were significant differences in quality over the data rate range of interest. Quality varied primarily in image resolution, but also in motion handling capability. Based on a tradeoff of all available features (including cost) the NEC 5000EX video codec was chosen for this application.

Modem

Operating at higher data rates compared to the baseline AMT allows for the use of a coherent detection scheme. This is due to the fact that the high close-in carrier phase noise on the satellite has a negligible effect on coherent demodulation techniques at higher data rates than the baseline rates for the AMT. The modem for this application

[7] The keyhole effect is symptomatic of 2-axis tracking mechanisms, when the tracking angle closely approaches one of the mechanisms rotational axes

has been designed to counteract the peculiarities of the K- and Ka-band aeronautical communications channel, including time varying frequency offsets, and signal outages typical of a mobile satellite communications channel. BPSK was chosen as the modulation with a coherent demodulator, and a concatenated coding scheme, a convolutional inner code (rate 1/2, constraint length 7) and a Reed-Solomon outer code (rate 239/256).

The demodulator loop parameters for this modem were optimized to track Doppler frequency offsets of up to *30* kHz, varying at 900 Hz per second. These offsets and rates of change are computed from the frequency bands in use and typical commercial aircraft maneuvers, The synchronization algorithms (carrier, bit, and decoder) were also optimized to allow re-synchronization within one second of signal presence after loss of signal, Commquest Technologies, Incorporated modified a commercially available satellite modem to meet the specifications for the aeronautical environment,

This modem has been tested both in the laboratory and the field. The maximum data rate for the modem is 2 Mbps. It achieves a bit error rate of 10^{-6} at an E_b/N_o of approximately 3.0 dB (AWGN, laboratory testing), A plot of the BER versus Eb/No performance of this modem over the AWGN channel is shown in Figure 14,

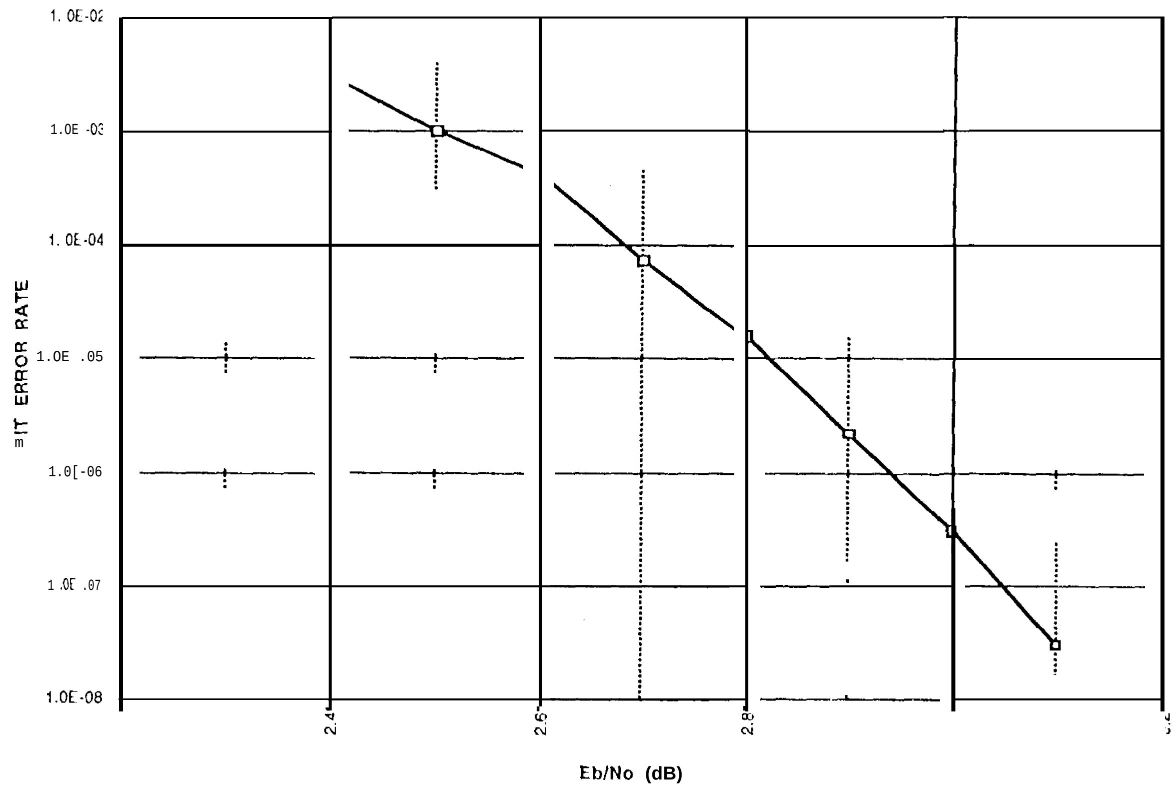

Figure 14 BAT Modem BER Performance

Antenna

The high gain aeronautical antenna employs an azimuth and elevation pointing system to allow it to track the satellite while the aircraft is maneuvering. The aeronautical antenna and radome have been developed by Electromagnetic Sciences (EMS) Technologies, Incorporated, The EMS antenna design utilizes a slotted waveguide array, is mechanically steered in both azimuth and elevation, and is designed to enable mounting on a variety of aircraft. The radome has been shaped with a peak height of 6.7 inches and a 27.6 inch diameter; roughly the size of the Sky Radio radome that has flown on United Airlines and Delta Airlines aircraft. The radome was designed for low loss at both frequency bands of operation, and to withstand the aerodynamic loads on a jumbo jet. Antenna installation requires a 3.5 inch diameter protrusion into the fuselage to allow the necessary signals to pass to and from the antenna. A picture of the antenna is shown in Figure 15 illustrating both the slotted waveguide and the polarizer, while the mounting of this antenna, including the radome, is shown in Figure 16.

The antenna is capable of tracking a full 360° in azimuth and -5° to zenith (90°) in elevation. The antenna has a transmit gain of 30 dBi and a receive G/T of O dB/°K. Circular polarization has been implemented[8] and there exists the capability to transmit up to 120 Watts of RF output power through the antenna. The actual dimensions of the combined transmit and receive array apertures are less than 16 inches wide, and less than 4.5 inches in height. The receive array has 161 elements with an ideal directivity of 30.4 dB at the band center. The receive 3 dB beamwidths are 4° in azimuth and 7.6° in elevation. The transmit array has 366 elements with an ideal directivity of 34.1 dB at the band center. The transmit 3 dB beamwidths are 2.6° in azimuth and 5.0° in elevation, Both arrays were designed to have maximum inband VSWR of 1.3:1 and the first sidelobe level at least 13 dB down from the peak.

The antenna tracking mechanism is required to maintain pointing within 0.5 dB of beam peak throughout all phases of flight, The antenna's narrowest beamwidth of 2.6° thus requires fine accuracy as the aircraft turns. The antenna positioner utilizes an elevation over azimuth mechanism, with a precision of a few hundredths of a degree. This positioner is controlled by a tracking algorithm that utilizes three sources of information: (1) a 3-axis inertial rate sensor, (2) the aircraft Inertial Navigation System (INS), and (3) the pilot signal strength feedback from a conical scanning of the beam, The rate sensor with a 50 Hz bandwidth and mounted on the main antenna assembly, provides the majority of the pointing information for the tracking system. A very low bandwidth (0.5 Hz), small displacement (0.5°) conical scan feedback control system is used to cancel, in the steady state, and continually adjust to any changes in the three axis inertial sensor offset and drift rates. The INS is used for satellite acquisition and correction of the rate sensor drift. The overall tracking system accommodates

[8] ACTS uses linear polarizations.

Figure 15 BAT Antenna

Figure 16 BAT Antenna Aircraft Mounted (Rockwell Saberliner 50) tracking rates up to 60 °/see and 30°/sec^2 in azimuth, and 30 °/see and 15°/sec2 in elevation,

Terminal Integration and Test

The expected performance over the satellite link is shown in the conservative link budgets for the forward (fixed station to aircraft) and return (aircraft to fixed station) links provided in Table 3. Not shown in the link budgets for simplicity is the forward link unmodulated pilot signal. These link budgets were computed for a data rate of 1,544 Mbps, and both directions have sufficient performance margins for the aeronautical channel. The performance predicted in these links budgets was verified during system integration and test. An interesting point to note is that due to exceeding design specifications, the terminal is able to achieve hi-directional data rates exceeding 1,544 Mbps, when the original design specification was for a data rate of 384 kbps.

The terminal has been successfully integrated into two different aircraft and has flown many flights, demonstrating the robustness of the terminal design, All operational aspects of the system, including the steerable beam tracking the aircraft have worked well. As part of one experiment, a live demonstration of the system capabilities was held on National Public TV [12]. In this demonstration, an Internet link to/from the ground was also integrated into the terminal.

SUMMARY

The development of ACTS, the AMT, and the BAT has proven to be an excellent proof-of-concept technology development for K- and Ka-band mobile satellite communications. Through this work, many advancements have been made in the area of K- and Ka-band mobile satellite communications. Through these developments, and the influx of experimenters with this equipment, it is hoped that NASA and JPL are contributing to the U.S. industrial community's technological advantage in this highly competitive market. It is envisioned, through the assistance of these terminal developments, that a commercial K- and Ka-band mobile satellite communications system will be a reality before the turn of the century. Indeed, the plethora of filings for systems at this band will ensure that this becomes a reality.

Table 3 BAT Experiment Link Budgets

PARAMETER	FORWARD LINK	RETURN LINK
	LA Fixed Station - BAT	BAT - LA Fixed Station
Terminal Transmitter Parameters		
EIRP, dBW	62.97	45.74
Pointing Loss, dB	-0.50	-0.50
Path Parameters		
Space Loss, dB	-213.84	-213.84
Frequency, GHz	29.634	29.634
Range, km	38000	38000
Atmospheric Attenuation, dB	-0.36	-0.36
Satellite Receive Parameters		
Polarization Loss, dB	-0.50	-4.10
Pointing Loss, dB	-0.22	-0.22
G/T, dB/°K	***20.56***	***14.28***
Bandwidth, MHz	900	900
Received C/NO, dB-Hz	97.12	70.01
transponder SNR_{IN}, dB	7.58	-19.54
Limiter Suppression, dB	-1.05	-1.05
Transponder SNR_{OUT}, dB	6.53	-20.57
Satellite Transmitter Parameters		
EIRP, dBW	56.08	64.33
Pointing Loss, dB	-0.24	-0.24
Path Parameters		
Space Loss, dB	-210.03	-210.03
Frequency, GHz	19.914	19.914
Range, km	38000	38000
atmospheric Attenuation, dB	-0.50	-0.50
Terminal Receive Parameters		
Polarization Loss, dB	-4.10	-0.50
Pointing Loss, dB	-0.50	-0.50
G/T, dB/°K	0.00	27.85
Downlink C/NO, dB-Hz	69.55	88.77
Overall C/N_o, dB-Hz	69.54	68.93
Required E_b/N_o (AWGN), dB (10^{-6} BER)	3.50	3.50
Fade Allowance, dB	0.00	0.00
Data Rate, kbps	1544.00	1544.00
Required C/N_o, dB-Hz	65.39	65.39
Link Margin, dB	***4.15***	***3.54***

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